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Growth of Tropical Legume Cover Crops as Influenced by Nitrogen Fertilization and Rhizobia

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Tropical legume cover crops are important components in cropping systems because of their role in improving soil quality. Information is limited on the influence of nitrogen (N) fertilization on growth of tropical legume cover crops grown on Oxisols. A greenhouse experiment was conducted to evaluate the influence of N fertilization with or without rhizobial inoculation on growth and shoot efficiency index of 10 important tropical cover crops. Nitrogen treatment were (i) 0 mg N kg^{-1} *(control or* N_0*), (ii) 0 mg N kg*$^{-1}$ + *inoculation with* Bradyrhizobial *strains (*N_1*), (iii) 100 mg N kg*$^{-1}$ + *inoculation with* Bradyrhizobial *strains (*N_2*), and (iv) 200 mg N kg*$^{-1}$ *of soil (*N_3*). The N* × *cover crops interactions were significant for shoot dry weight, root dry weight, maximal root length, and specific root length, indicating that cover crop performance varied with varying N rates and inoculation treatments. Shoot dry weight is considered an important growth trait in cover crops and, overall, maximal shoot dry weight was produced at 100 mg N kg*$^{-1}$ + *inoculation treatment. Based on shoot dry-weight efficiency index, cover crops were classified as efficient, moderately efficient, and inefficient in N-use efficiency. Overall, the efficient cover crops were lablab, gray velvet bean, jack bean, and black velvet bean and inefficient cover crops were pueraria, calopo, crotalaria, smooth crotalaria, and showy crotalaria. Pigeonpea was classified as moderately efficient in producing shoot dry weight.*

Keywords Maximum root length, root dry weight, shoot dry weight, specific root length

Introduction

A major part of the cultivated land area in South America is dominated by acidic soils with poor fertility, and these are major constraints for crop production in these areas (Fageria and Baligar 2003, 2008; Fageria 2009). Many plantation crops in this region are grown on sloping land with wide spacing. In such management systems, soil and nutrient loss by erosion is a major soil degradation factor. Coplanting of cover crops at the time of establishment of perennial fruit trees and growing cover crops between periods of normal

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annual crop production cycles are important management strategies for reducing nutrient and soil loss by erosion, thereby halting further soil degradation.

Using cover crops in cropping systems in improving soil fertility is an important strategy in this direction (Fageria, Baligar, and Jones 2011). Cover crops provide soil protection from wind and soil erosion; conserve soil moisture; improve soil physical, chemical, and biological properties; recycle nutrients from lower to upper soil layers; and control of pests such as pathogenic nematodes (Fageria et al. 2011; Fageria, Baligar, and Bailey 2005). Other beneficial effects of cover crops are that they build organic matter, smother weeds, improve soil tilth, impede the formation of crust layers, and stabilize N supply (Teasdale 1998; Fageria, Baligar, and Jones 2011). However, beneficial effects depend on the selection of appropriate cover crops and their management (Fageria, Baligar, and Jones 2011). Hence, understanding of their agronomy and physiology is fundamental for their use in sustainable cropping systems. Growth and development of a crop (physiological aspects) is determined genetically as well as influenced by environmental variables (Fageria et al. 2011; Fageria, Baligar, and Bailey 2005; Baligar and Fageria 2007). Many of the tropical legumes weakly fix N_2 and show variable responses to inoculation; thus, the poor N_2 fixation is probably attributed to the difficulty of establishing effective symbiosis in the field and to plant genetic variability in the capacity to fix N (Fageria et al. 2011). Soil groups that predominant in South America are Oxisols, Ultisols, and Inceptisols, which are acidic and have low levels of essential nutrients (Baligar et al. 2004), and in particular these soils have very low soil fertility and lack adequate levels of N to support good crop growth (Giller 2001; Houngnandan et al. 2001). Bad management and nonapplication of organic manure and fertilizers for highly weathered tropical soils have resulted in lowering soil fertility to support good crop growth (Giller 2001; Hartemink 2003; Fageria, Baligar, and Jones 2011). Soil fertility requirements for establishment and production of legume cover crops in acidic soils have not been fully determined. Reduction of soil acidity and addition of N promote excellent early growth of legume cover crops (Fageria and Baligar 1997). Reduction of N_2 fixation is usually associated with N fertilization (Streeter 1988), but there is variation in this response depending on the host–rhizobium association (Seguin et al. 2001). Seguin et al (2001) states that moderate N fertilization may benefit legumes with slow nodulation development and/or low N_2 fixation levels and further applied N increased herbage yield and in some cases increased nodulation and N_2 fixation. Application of costly inorganic fertilizer increases the cost of production. Therefore use of legume cover crops or addition of green manure crops reduces the need for high N fertilizer inputs and further reduces the need for N fertilizer by the succeeding crop (Fageria 2007). Highly weathered tropical soils also lack the right types and levels of rhizobiums to promote adequate N_2-fixation capacity by tropical legume cover crops. However, data are limited on influence of inoculation and/or chemical N application on tropical legume cover crops grown on acidic and infertile Oxisols. Root length and rooting patterns are important morphological feature that impact plants' ability to take up nutrients and water (Russell 1977). Plant species with longer root length are capable of taping nutrients from deeper layers of soil. Rooting pattern (dry weight, root length, specific root length) vary among species, and information is lacking on rooting pattern of legume cover crops in soil with varying levels of N and rhizobium inoculants. The objective of this study was to evaluate growth (shoot and root growth, shoot production efficiency) of principal tropical cover crops as influenced by N fertilization and rhizobial inoculation. This information can be useful in improving production of these crops and, consequently, their incorporation into farming systems wherever possible.

Materials and Methods

Soil Properties, Nitrogen Treatments, and Basic Fertilization

The soil used in the experiment was Oxisol with following chemical and physical properties before imposing acidity treatments: pH in H_2O 4.3, calcium (Ca) 0.90 $cmol_c\ kg^{-1}$, magnesium (Mg) 0.40 $cmol_c\ kg^{-1}$, aluminum (Al) 0.2 $cmol_c\ kg^{-1}$, phosphorus (P) 0.8 mg kg^{-1}, potassium (K) 47 mg kg^{-1}, copper (Cu) 1.6 mg kg^{-1}, zinc (Zn) 0.70 mg kg^{-1}, iron (Fe) 40 mg kg^{-1}, manganese (Mn) 15 mg kg^{-1}, organic matter 21 g kg^{-1}, clay 680 g kg^{-1}, silt 113 g kg^{-1}, and sand 207 g kg^{-1}. The soil analytical methods used are described in manual of soil analysis (EMBRAPA 1997).

The N levels used were (i) 0 mg N kg^{-1} (control or N_0), (ii) 0 mg N kg^{-1} + inoculation with *Bradyrhizobial* strains (N_1), (iii) 100 mg N kg^{-1} + inoculation with *Bradyrhizobial* strains (N_2), and (iv) 200 mg N kg^{-1} of soil (N_3). A randomized complete block, split-plot design was used. Fourteen strains from the Brazilian (SEMIA) culture collection of rhizobia were used as inoculants for the 10 cover crops. Table 1 provides information on the strains, as well as on the cover crops for which they are recommended. The N levels were the main plots and cover crop species were subplots. Treatment combinations were replicated three times. All the plots received a basal application of 200 mg P pot^{-1}, and 200 mg K pot^{-1} was applied, as triple superphosphate and potassium chloride, respectively. Each pot also received 10 g dolomitic lime 4 weeks before sowing of cover crops, and the liming material used had 32.9% calcium oxide (CaO), 14.0% magnesium oxide (MgO), and neutralizing power of 85%. Pots were subjected to four cycles of wetting and drying to ensure uniform mixing of the amendments.

Table 1
Bradyrhizobal strains used in inoculation of cover crop seeds and 100-seed weight

Cover crop	*Bradyrhizobial* strain(s)[a]	Reference	Hundred-seed weight (g)
1. Crotalaria	SEMIA 5156 SEMIA 6158	This work	1.90
2. Smooth crotalaria	SEMIA 5156 SEMIA 6158	This work	0.80
3. Showy Crotalaria	SEMIA 6156 SEMIA 6158	Menna et al. (2006)	1.82
4. Calopo	SEMIA 6152	Menna et al. (2006)	1.53
5. Pueraria	SEMIA 6175	Menna et al. (2006)	1.44
6. Pigeonpea	SEMA 6156	Menna et al. (2006)	9.21
7. Lablab	SEMIA 662	Menna et al. (2006)	23.02
8. Black velvet bean	SEMIA 6158	Menna et al. (2006)	73.86
9. Gray velvet bean	SEMIA 6158	Menna et al. (2006)	95.68
10. Jack bean	SEMIA 6152 SEMIA 695	Menna et al. (2006)	137.29

[a]Registration number of the bacterial strains on the Brazilian Rhizobium Culture Collection (SEMIA).

Table 2
Common and scientific names of 10 legume cover crop species used in the experiment

Common name	Scientific name
1. Crotalaria (short-flowered crotalaria)	*Crotalaria breviflora* DC.
2. Crotalaria (smooth crotalaria)	*Crotalaria mucronata (C. pallida* Aiton)
3. Crotalaria (showy Crotalaria)	*Crotalaria spectabilis* Roth
4. Calopo	*Calopogonium mucunoides*
5. Pueraria (tropical kudzu)	*Pueraria phaseoloides* Roxb.
6. Pigeonpea (black)	*Cajanus cajan* L. Millspaugh
7. Lablab	*Lablab purpureus* L. Sweet (*Dolichos Lablab*)
8. Black velvet bean (black mucuna bean)	*Mucuna aterrima* (Piper & Tracy) Holland (*M. Pruriens*, L DC.)
9. Gray velvet bean (Bengal bean, gray mucuna bean)	*Mucuna cinereum* L.
10. Jack bean	*Canavalia ensiformis* L. DC.

Cover Crop Species and Growing Conditions

A greenhouse experiment was conducted to evaluate shoot and root growth of 10 tropical cover crops (Table 2). The experiment was conducted in plastic pots with 6 kg soil, and 10 seeds of each cover crop were planted per pot; after germination, four healthy plants were maintained per pot. The common and scientific names of these cover crops are given in Table 2. In the greenhouse during growth the mean minimal air temperature ranged from 17.1 to 19.3 °C, maximum temperature ranged from 29.2 to 29.9 °C, and mean relative humidity ranged from 51.6% to 77.0%. Plants were harvested at an age of 49 days after sowing. Roots from each pot were washed manually, and maximal root length was measured. Harvested material was washed in distilled water several times and dried at 70 °C to a constant weight.

Observation and Data Analysis

Specific root length (SRL, cm g^{-1} root dry wt) and shoot dry weight efficiency index (SDEI) were calculated by using the following equations:

$$\mathrm{SRL} = \frac{\textit{Maximum root length in cm}}{\textit{Root dry weight in g}}$$

$$\mathrm{SDEI} = \frac{X_1}{X_2} \times \frac{Y_1}{Y_2}$$

where X_1 is shoot dry weight at zero N level, X_2 is average shoot dry weight of 10 cover crops at zero N level, Y_1 is shoot dry weight at a given N rate, and Y_2 is average shoot dry weight of 10 cover crops at a given N rate with or without rhizobal inoculants. Based on SDEI, cover crops were classified as inefficient, moderately efficient, and efficient. Cover crops that had shoot dry wt. efficiency index (SDEI) values ranging from 0 to

0.50 were classified as inefficient, values in the range of 0.50 to 1.0 were classified as moderately efficient, and values greater than 1.0 were classified as efficient. This is an arbitrary classification index; however, this index separates stable and efficient cover crops at lower and higher rates of applied N (Fageria 2009).

Data were analyzed by analysis of variance (ANOVA) to evaluate treatment effects, and means were compared by Tukey's test at the 5% probability level. Shoot dry weight was correlated with maximal root length, root dry weight, specific root length, root-to-shoot ratio, and shoot dry-weight efficiency index by regression equations. An appropriate regression model was selected on the basis of R^2 values.

Results and Discussion

Shoot Dry Weight

The N × cover crop interaction for shoot dry weight was significant, indicating that different responses of cover crops exists for varying levels of applied N and *Bradyrhizobial* inoculants (Table 3). At 0 mg N kg^{-1} (N_0) treatment shoot dry weight varied from 0.98 g

Table 3
Shoot dry weight of 10 tropical cover crops as influenced by nitrogen and *Bradyrhizobial* inoculants

	Shoot dry weight (g plant^{-1})				
Cover crop	N_0	N_1	N_2	N_3	Average
1. Crotalaria	0.98e	1.36de	1.95g	1.66e	1.48f
2. Smooth crotalaria	2.89bcd	3.05cd	3.84ef	3.56cd	3.33de
3. Showy Crotalaria	3.59bc	2.67cde	5.83d	4.00c	4.02cd
4. Calopo	2.27cde	3.01cd	2.78fg	2.13de	2.55e
5. Pueraria	1.25de	1.17e	1.21g	0.73e	1.09f
6. Pigeonpea	4.64b	4.46c	4.69de	3.56cd	4.33c
7. Lablab	10.89a	9.82b	11.89b	13.73a	11.58a
8. Black velvet bean	9.42a	9.16b	9.33c	13.37a	10.32b
9. Gray velvet bean	9.52a	11.90a	12.90b	12.66a	11.74a
10. Jack bean	9.85a	13.23a	16.73a	8.16b	11.99a
Average	5.53c	5.98bc	7.11a	6.36b	
F-test					
N rate (N)	**				
Cover crops (C)	**				
N × C	**				
CVN (%)	11.64				
CVC (%)	10.89				

**Significant at the 1% probability level.

Notes. Means in the same column followed by the same letter are not significantly different at the 5% probability level by Tukey's test. Average values were compared in the same line for significant differences among N rates. $N_0 = 0$ mg N kg^{-1}; $N_1 = 0$ mg N kg^{-1} + *Bradyrhizobial* inoculants; $N_2 = 100$ mg N kg^{-1} + *Bradyrhizobial* inoculants; and $N_3 = 200$ mg N kg^{-1}.

plant^{-1} produced by crotalaria to 10.89 g plant^{-1} produced by lablab, with an average value of 5.53 g plant^{-1}. When seeds were treated with *Bradyrhizobial* inoculants (0 mg N kg^{-1} + inoculated or N_1), pueraria produced minimal shoot dry weight and jack bean produced maximal shoot dry weight. At N_2 treatment (100 mg N kg^{-1} + *Bradyrhizobial* inoculants or N_2), the differences in responses of these two cover crops were similar. However, when N rate was increased to 200 mg kg^{-1} (N_3) treatment, pueraria produced minimal shoot dry weight, but maximal shoot dry weight was produced by lablab. Across four N treatments, maximal shoot dry weight was produced by jack bean and minimal shoot dry weight was produced by pueraria. Overall, maximal shoot dry weight was produced at N_2 treatment (100 mg N kg^{-1} + inoculant). The increase in shoot dry weight with the N_2 treatment was 29% compared to the control treatment (N_0). Variation in shoot dry weight among tropical legume cover crops has also been reported by Fageria et al. (2011). Similarly, improvement in shoot dry weight of annual crops (cereals and legumes) with the addition of N was associated with increase in leaf area with the addition of N and improvement in photosynthetic efficiency of plants (Marschner 1995; Fageria, Baligar, and Jones 2011). Engles and Marschner (1995) and Fageria, Baligar, and Clark (2006) reported that N greatly influences leaf growth, leaf area duration, and photosynthetic rate per unit leaf area to control production of carbohydrates and other photosynthetic products (source activity) and influences number and sizes of vegetative and reproductive storage organs (sink capacity). Figure 1 shows the increases in plant foliage and dark green color with the addition of N + *Bradyrhizobial* inoculants and N treatments. Plants in the control treatment showed N deficiency with yellow color in the older leaves.

One of the striking features of our study was the importance of seed size. Seed weight was positively and significantly correlated with shoot dry weight (Figure 2). Variation in

Figure 1. Lablab shoot growth at different nitrogen treatments. Left to right: 0 mg N kg^{-1}, 0 mg N kg^{-1} + *Bradyrhizobial* inoculants, 100 mg N kg^{-1} + *Bradyrhizobial* inoculants, and 200 mg N kg^{-1}.

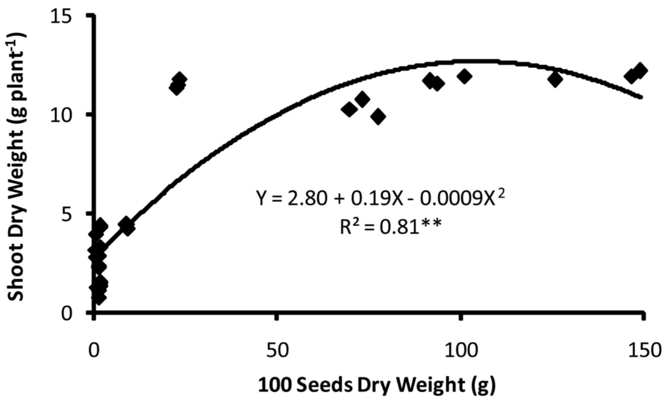

Figure 2. Relationship between hundred-seed weight and shoot dry weight.

shoot dry weight was 81% associated with variation in seed weight. Based on a quadratic equation, maximal shoot dry weight was achieved at the 104 g weight of 100 seeds. Species such as jack bean, gray velvet bean, black velvet bean, and lablab have heavier seed weights (Table 1) and greater shoot dry weight (Table 3). Similarly, pueraria, crotalaria, and smooth crotalaria have lowest seed weights (Table 1) and lowest shoot dry weight (Table 3). Fageria et al. (2009) reported that seed weight of tropical legume cover crops was positively related to shoot dry-weight efficiency index.

Maximal Root Length

The N $\times$ cover crops root length interaction was significant for root length (Table 4), indicating that some crop species were highly responsive to the applied N and *Bradyrhizobial* inoculants whereas other were not. In the control treatment (N_0), maximal root length varied from 22 cm produced by showy crotalaria to 33 cm produced by smooth crotalaria, with an average value of 26.17 cm. At N_1 (0 mg N kg^{-1} + *Bradyrhizobial* inoculants) and N_2 treatment (100 mg N kg^{-1} + *Bradyrhizobial* inoculants) minimal root length was produced by black velvet bean and maximum root length was produced by pigeon pea. At N_3 (200 mg N kg^{-1}) treatment the situation changed and minimal root length of 20 cm was produced by jack bean and maximum root length of 33.33 cm was produced by gray velvet bean. Across four N treatments, minimal root length of 23.08 cm was produced by jack bean and maximal root length of 30.83 cm was produced by calopo, with an average value of 26.99 cm. Variation in root length is genetically controlled and varied among plant species, and it is also influenced by environmental factors (Eghball et al. 1993; Costa et al. 2002; Fageria, Baligar, and Clark 2006).

Root Dry Weight

Root dry weight had a significant N $\times$ cover crop species interaction (Table 5), indicating variation in root dry weight with the variation in N and *Bradyrhizobial* inoculants. In the control treatment (N_0) shoot dry weight varied from 0.16 g plant^{-1} produced by pueraria to 2.01 g plant^{-1} produced by gray velvet bean, with an average value of 0.72 g plant^{-1}. These two cover crops also produced minimal and maximal root dry weights at N_1

Table 4
Maximal root length of 10 tropical cover crops as influenced by nitrogen and *Bradyrhizobial* inoculants

	Maximal root length (cm)				
Cover crop	N_0	N_1	N_2	N_3	Average
1. Crotalaria	29.00ab	24.00cde	24.67cd	20.67e	24.58b
2. Smooth crotalaria	33.00a	25.33bcd	30.67ab	28.67abc	29.42a
3. Showy Crotalaria	22.00d	21.67de	29.33bc	26.33cd	24.83b
4. Calopo	27.67bc	29.33ab	34.00ab	32.33ab	30.83a
5. Pueraria	23.33cd	24.33cde	24.00d	28.00bc	24.92b
6. Pigeonpea	30.00ab	30.67a	34.33a	23.00de	29.50a
7. Lablab	26.67bcd	29.33ab	31.67ab	26.33cd	28.50a
8. Black velvet bean	25.33bcd	20.00e	18.33e	32.33ab	24.00b
9. Gray velvet bean	27.67bc	29.33ab	30.67ab	33.33a	30.25a
10. Jack bean	23.67cd	27.67abc	21.00de	20.00e	23.08b
Average	26.17a	26.83a	27.87a	27.87a	26.99
F-test					
N rate (N)	NS				
Cover crops (C)	**				
N × C	**				
CVN (%)	9.27				
CVC (%)	6.75				

**, NS Significant at the 1% probability level and not significant, respectively.

Notes. Means in the same column followed by the same letter are not significantly different at the 5% probability level by Tukey's test. Average values were compared in the same line for significant differences among N rates. $N_0 = 0$ mg N kg^{-1}; $N_1 = 0$ mg N kg^{-1} + *Bradyrhizobial* inoculants; $N_2 = 100$ mg N kg^{-1} + *Bradyrhizobial* inoculants; and $N_3 = 200$ mg N kg^{-1}.

(0 mg N kg^{-1} + inoculants) and N_2 (100 mg N kg^{-1} + inoculant) treatments. However, at N_3 (200 mg N kg^{-1}) treatment, minimum root dry weight was produced by crotalaria, and maximum root dry weight was produced by black velvet bean. Across four N levels, minimum root dry weight was produced by crotalaria and pueraria, and maximum root dry weight was produced by gray velvet bean. Overall, gray velvet bean produced about 12-fold more root dry weight compared with minimum root dry-weight-producing cover crops crotalaria and pueraria. Root dry weight is an important trait in improving organic-matter content of the soil as well as in the absorption of water and nutrients (Sainju, Singh, and Whitehead 1998; Fageria, Baligar, and Clark 2006). Vigorous root systems also assimilate large amounts of leaching nutrients such as N and provide them to the succeeding economic crops (Kristensen and Thorup-Kristensen 2004; Feaga et al. 2010). Root dry weight had significant positive association with shoot dry weight (Figure 3). Figures 4–6 show root growth of showy crotalaria, calopo, and lablab, respectively. Root growth varied with N treatments, and overall, more vigorous root system was produced at N_2 (100 mg N kg^{-1} + inoculant) treatment compared with other three N treatments in three cover crops. Baligar, Fageria, and Elrashidi (1998) reported that root dry weight of legume crops was heavier with the addition of N compared to that without N application treatment.

Table 5

Root dry weight of 10 tropical cover crops as influenced by nitrogen and *Bradyrhizobial* inoculants

	Root dry weight (g plant^{-1})				
Cover crop	N_0	N_1	N_2	N_3	Average
1. Crotalaria	0.18d	0.13f	0.19d	0.14d	0.16e
2. Smooth crotalaria	0.23d	0.48ef	0.81bc	0.38d	0.47d
3. Showy Crotalaria	0.48bcd	0.51ef	0.77bc	0.43d	0.55d
4. Calopo	0.30cd	0.42ef	0.46cd	0.31d	0.37d
5. Pueraria	0.16d	0.15f	0.15d	0.16d	0.16e
6. Pigeonpea	0.73b	0.68de	0.48cd	0.21d	0.53d
7. Lablab	0.74b	1.42bc	1.72a	1.64b	1.38b
8. Black velvet bean	1.66a	1.74ab	0.50cd	2.08a	1.49b
9. Gray velvet bean	2.01a	1.91a	1.84a	1.71ab	1.87a
10. Jack bean	0.65bc	1.10cd	1.12b	0.94c	0.95c
Average	0.72a	0.85a	0.80a	0.80a	0.79
F-test					
N rate (N)	NS				
Cover crops (C)	**				
N × C	**				
CVN (%)	25.59				
CVC (%)	19.71				

**, NS Significant at the 1% probability level and not significant, respectively.

Notes. Means in the same column followed by the same letter are not significantly different at the 5% probability level by Tukey's test. Average values were compared in the same line for significant differences among N rates. $N_0 = 0$ mg N kg^{-1}; $N_1 = 0$ mg N kg^{-1} + *Bradyrhizobal* inoculants; $N_2 =$ 100 mg N kg^{-1} + *Bradyrhizobial* inoculants; and $N_3 = 200$ mg N kg^{-1}.

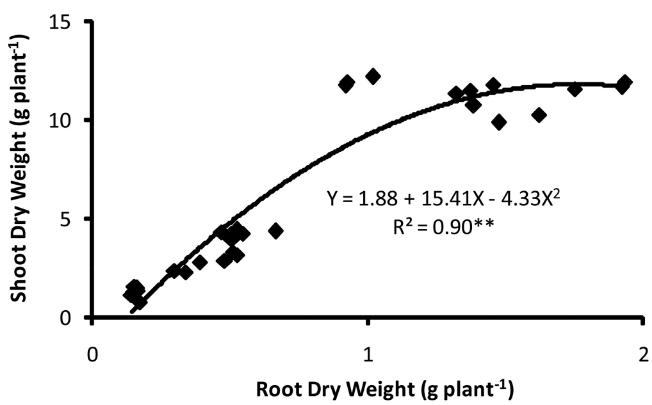

Figure 3. Relationship between root dry weight and shoot dry weight.

Figure 4. Showy crotalaria root growth at different nitrogen treatments. Left to right: 0 mg N kg^{-1}, 0 mg N kg^{-1} + *Bradyrhizobial* inoculants, 100 mg N kg^{-1} + *Bradyrhizobial* inoculants, and 200 mg N kg^{-1}.

Specific Root Length (SRL)

Because direct measurement of root surface area and volume has been problematic, specific root length (SRL, root length divided by root dry weight) has been an excellent surrogate for surface area-to-volume ratio (Eissenstat et al. 2000; Zobel 2005). Hence, we determined specific root length of 10 cover crops, and results are presented in Table 6. The SRL was significantly affected by N, cover crops, and N $\times$ cover crops interaction. Maximum SRL was achieved at N_3 treatment (200 mg N kg^{-1} soil), and at this N level pueraria produced maximum SRL and black velvet bean produced minimum SRL. Overall, maximum SRL was also produced pueraria and minimum by gray velvet bean. This may be due to maximum and minimum root dry weights produced by these two cover crops across N levels. The SRL had a significant negative quadratic relationship with shoot dry weight (Figure 7).

Figure 5. Calopo root growth at different N treatments. Left to right: 0 mg N kg^{-1}, 0 mg N kg^{-1} + *Bradyrhizobial* inoculants, 100 mg N kg^{-1} + *Bradyrhizobial* inoculants, and 200 mg N kg^{-1}.

Shoot-to-Root Ratio

Shoot-to-root ratio of 10 cover crop species was significantly influenced by N, cover crops, and N × cover crops interaction (Table 7). Overall, maximum shoot-to-root ratio was at N_2 and N_3 treatments. The average increase in shoot-to-root ratio was 13% at N_2 treatment and 9% with the N_3 treatment compared to the control treatment. Greater shoot-to-root ratio at greater N levels indicates higher shoots had more priority for photosynthate accumulation than roots (Fageria, Baligar, and Clark 2006). Davidson (1969) reported that increased N rate increased shoot-to-root ratio in crop plants. Across N treatments, cover crop jack bean produced maximal shoot-to-root ratio, and gray velvet bean produced minimal shoot-to-root ratios. Variation in shoot-to-root ratio among field crops

Figure 6. Lablab root growth at different nitrogen treatments. Left to right: 0 mg N kg^{-1}, 0 mg N kg^{-1} + *Bradyrhizobial* inoculants, 100 mg N kg^{-1} + *Bradyrhizobial* inoculants, and 200 mg N kg^{-1}.

is due to differences in their shoot and root dry-weight production (Fageria, Baligar, and Clark 2006), which is related to their photosynthetic efficiency (Eastin and Sullivan 1984).

Classification of Cover Crops in Nitrogen-Use Efficiency

Shoot dry-weight production efficiency had a significant positive association with shoot dry weight (Figure 8). Hence, this index was used in classifying cover crops in N-use efficiency (Table 8). Cover crops' N-use efficiency varied from N level to N level and also among crop species. Cover crops lablab, black velvet bean, gray velvet bean, and jack bean were efficient in N-use efficiency at all three N levels. In contrast, cover crop species crotalaria, smooth crotalaria, showy crotalaria, calopo, and pueraria were inefficient in N-use efficiency. Cover crop pigeon pea was moderately efficient in N-use efficiency. Variation in legume crops in N-use efficiency is widely reported in the literature (Fageria and Baligar 2005; Fageria, Baligar, and Clark 2006; Fageria, Baligar, and Jones 2011). This variation may be related to greater uptake and/or greater utilization of N by crop species (Baligar, Duncan, and Fageria 1990; Baligar, Fageria, and He 2001).

Table 6
Specific root length of 10 tropical cover crops as influenced by nitrogen and *Bradyrhizobial* inoculants

	Specific root length (cm g^{-1} root dry weight)				
Cover crop	N_0	N_1	N_2	N_3	Average
1. Crotalaria	161.11a	195.28a	130.42ab	145.15ab	157.99a
2. Smooth crotalaria	108.01a	56.62b	38.19cd	91.63bc	73.61bc
3. Showy Crotalaria	47.17b	43.76b	38.76cd	66.01cd	48.92cd
4. Calopo	99.14a	69.19b	81.25bc	118.25bc	94.21b
5. Pueraria	145.96a	172.43ab	158.06a	193.91a	167.59a
6. Pigeonpea	43.41b	45.24b	74.17bcd	110.67bc	68.37bc
7. Lablab	35.76b	20.58b	18.87d	16.43d	22.91de
8. Black velvet bean	15.64b	11.54b	39.71cd	15.86d	20.69de
9. Gray velvet bean	13.74b	15.51b	16.67d	20.00d	16.48e
10. Jack bean	37.33b	25.56b	18.87d	21.28d	25.76de
Average	70.73ab	65.57ab	61.50b	79.92a	69.43
F-test					
N rate (N)	*				
Cover crops (C)	**				
N × C	**				
CVN (%)	26.24				
CVC (%)	32.13				

*, **Significant at the 5 and 1% probability levels, respectively.

Notes. Means in the same column followed by the same letter are not significantly different at the 5% probability level by Tukey's test. Average values were compared in the same line for significant differences among N rates. $N_0 = 0$ mg N kg^{-1}; $N_1 = 0$ mg N kg^{-1} + *Bradyrhizobial* inoculants; $N_2 = 100$ mg N kg^{-1} + *Bradyrhizobial* inoculants; and $N_3 = 200$ mg N kg^{-1}.

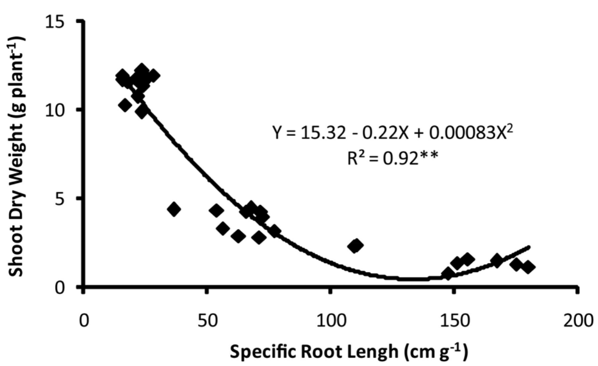

Figure 7. Relationship between specific root length and shoot dry weight.

Table 7
Shoot-to-root ratio of 10 tropical cover crops as influenced by nitrogen and *Bradyrhizobal* inoculants

	Shoot-to-root ratio				
Cover crop	N_0	N_1	N_2	N_3	Average
1. Crotalaria	5.45c	10.90ab	10.18bc	11.60ab	9.53bc
2. Smooth crotalaria	9.4bc	6.75abc	4.82c	9.99bc	7.72bcd
3. Showy Crotalaria	7.64c	5.31c	7.71c	9.73bc	7.60bcd
4. Calopo	7.88c	7.14abc	6.24c	7.34bc	7.15cd
5. Pueraria	7.86c	8.05abc	7.95c	6.05c	7.48bcd
6. Pigeonpea	6.54c	6.59bc	10.02bc	16.74a	9.97b
7. Lablab	14.62ab	6.87abc	7.14c	8.59bc	9.30bc
8. Black velvet bean	5.78c	5.29c	19.97a	6.55bc	9.40bc
9. Gray velvet bean	4.73c	6.28bc	7.02c	7.57bc	6.40d
10. Jack bean	15.54a	12.16a	15.28ab	8.74bc	12.93a
Average	8.54ab	7.53b	9.63a	9.29a	8.75
F-test					
N rate (N)	*				
Cover crops (C)	**				
N × C	**				
CVN (%)	22.20				
CVC (%)	23.74				

*, **Significant at the 5 and 1% probability levels, respectively.

Notes. Means in the same column followed by the same letter are not significantly different at the 5% probability level by Tukey's test. Average values were compared in the same line for significant differences among N rates. $N_0 = 0$ mg N kg^{-1}; $N_1 = 0$ mg N kg^{-1} + *Bradyrhizobial* inoculants; $N_2 = 100$ mg N kg^{-1} + *Bradyrhizobial* inoculants; and $N_3 = 200$ mg N kg^{-1}.

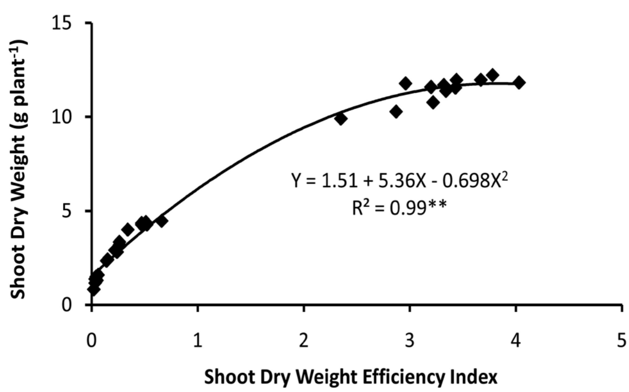

Figure 8. Relationship between shoot dry-weight efficiency index and shoot dry weight.

Table 8
Classification of 10 tropical cover crops as efficient, moderately efficient, and inefficient based on shoot dry-weight production efficiency index as influenced by nitrogen and *Bradyrhizobial* inoculants

	Shoot dry-weight production efficiency index			
Cover crop	N_1	N_2	N_3	Average
1. Crotalaria	0.05d(IE)	0.04d(IE)	0.04c(IE)	0.04e(IE)
2. Smooth crotalaria	0.28d(IE)	0.29d(IE)	0.28c(IE)	0.28de(IE)
3. Showy crotalaria	0.53d(ME)	0.41d(IE)	0.41c(IE)	0.45de(IE)
4. Calopo	0.16d(IE)	0.14d(IE)	0.17c(IE)	0.17de(IE)
5. Pueraria	0.04d(IE)	0.02d(IE)	0.03(IE)	0.03e(IE)
6. Pigeonpea	0.55d(ME)	0.46d(IE)	0.55c(ME)	0.52d(ME)
7. Lablab	3.29b(E)	4.27a(E)	3.60a(E)	3.72a(E)
8. Black velvet bean	2.23c(E)	3.61ab(E)	2.81b(E)	2.88c(E)
9. Gray velvet bean	3.12b(E)	3.42b(E)	3.32ab(E)	3.28bc(E)
10. Jack bean	4.19a(E)	2.28c(E)	3.47ab(E)	3.31ab(E)
Average	1.44a	1.49a	1.46a	1.47
F-test				
N rate (N)	NS			
Cover crops (C)	**			
N × C	**			
CVN (%)	7.07			
CVC (%)	18.77			

*,**,NS Significant at the 5 and 1% probability levels and not significant, respectively.

Notes. Means in the same column followed by the same letter are not significantly different at the 5% probability level by Tukey's test. Average values were compared in the same line for significant differences among N rates. $N_1 = 0$ mg N kg^{-1} + *Bradyrhizobial* inoculants; $N_2 = 100$ mg N kg^{-1} + *Bradyrhizobial* inoculants; and $N_3 = 200$ mg N kg^{-1}. IE, inefficient; ME, moderately efficient; and E, efficient.

Conclusions

Cover crops are important component of cropping systems in improving soil quality and consequently crop yields. Results of this study show that tropical legume cover crops differ significantly in shoot dry weight, root length, and root dry weight when grown on a Brazilian Oxisol. Overall, maximal growth of roots and shoots was achieved at 100 mg N kg^{-1} + inoculant treatment, suggesting that N application is essential to get maximum benefit from cover crops in a cropping system. However, inoculation of these cover crops with suitable *Bradyrhizobial* can reduce N requirements. The most efficient cover crops for tropical soils are lablab, black velvet bean, gray velvet bean, and jack bean.

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